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LONG TERM STABILITY ASSESSMENT OF A ROOM AND PILLAR COAL MINE – A FRANCO/SOUTH AFRICAN APPROACH

CAUVIN Maxime^{1,3}, VAN DER MERWE J. Nielen², DIDIER Christophe³, MOTHIBI Oupa²

¹ LAEGO – Ecole des Mines de Nancy, Parc de Saurupt – CS 14234 – 54042 Nancy Cedex – France ;
maxime.cauvin@mines-nancy.org

² Mining Department, University of Pretoria, Brooklyn Road – Pretoria 2001 – Republic of South Africa;
nielen.vandermerwe@up.ac.za; oupa.mothibi@up.ac.za

³ INERIS, Parc Alata – BP 2 – 60550 Verneuil-en-Halatte – France ; christophe.didier@ineris.fr

ABSTRACT: As abandoned mines, “mature” mines are very challenging for geotechnical engineers with respect to long term stability issues that are part of the management of the “post-mining” phase. This paper presents a risk assessment study that has been carried out in an underground coal mine by French and South African experts in the framework of the PROTEA Programme funded by the institutions of these two countries. This study associates classical geotechnical methods of pillar stability analysis with tools allowing an integration of uncertainties in the analysis and a probabilistic expression of hazard issues. Technical regulations, aimed at managing the consequences a pillar collapse may have on public safety and future land use management, are also discussed.

KEYWORDS: Mature mine, Pillar failure, Surface stability, Uncertainty, Probabilistic analysis.

RÉSUMÉ : De la même manière que pour les mines abandonnées, les mines « matures » posent des problèmes aux ingénieurs en terme de stabilité à long terme des terrains de surface, problématique qui constitue l’un des volets de la gestion de la phase dite d’ « Après-mine ». Cet article présente une étude qui a été réalisée conjointement par des chercheurs français et sud-africains dans le cadre du programme de recherche PROTEA soutenu par les institutions de ces deux pays. Il présente l’association des méthodes d’analyse de stabilité classiques utilisées dans le domaine de la géotechnique, à des outils permettant l’intégration des incertitudes dans l’étude et l’expression de l’aléa sous une forme probabiliste. Des recommandations techniques permettant de limiter les conséquences qu’une rupture souterraine de pilier pourrait avoir vis-à-vis de la sécurité des travailleurs ou des populations de surface, ainsi que vis-à-vis de l’occupation future des terrains, sont également proposées.

MOTS-CLEFS : Mine mature, Rupture de pilier, Stabilité des terrains de surface, Incertitude, Analyse probabiliste.

1. Introduction

“Mature mines” constitute an important challenge today in the Republic of South Africa. The current reserves of those mines have almost been depleted and the challenge for mining engineers is to stretch the exploitation to its limit in order to save time until new coal fields have been prepared to replace the current production. Such an extent in mining should however respect different issues regarding both the current safety of workers and the management of the “post-mining” phase.

The issue of “post-mining” management is today clearly international. All over the world, mining countries face, or start to face, problems related to their old mining activity. However, even if

national approaches are progressively developed, there is still a total lack of formalism, at an international scale, on the methods used to assess and manage the “post-mining” hazards.

The paper presented herein illustrates a risk assessment that has been undertaken by both French and South African researchers. France has worked for about ten years on “post-mining” issues and the methodology developed with the aim of predicting, preventing and managing the potential hazards related to the disused mining activity, is today successfully applied. On its side, the Republic of South Africa, where mining is still valuable, is currently facing problems similar to the ones in France and is trying to anticipate them for the near future.

The case of application being chosen concerns the evaluation of the likelihood of a surface collapse above a South African room and pillar coal mine. Technical regulations aimed at managing the consequences it may have on public safety and future land use management will also be discussed.

2. Presentation of the mine

The mine being studied is located in the Mpumalanga Province. It belongs to the Witbank coal basin. The geological sequence in the area includes five coal seams but only one is currently exploited. The mine can be described as a shallow mine (17 to 88 meters below surface) exploited using the room and pillar mining method.

The study focuses in an area where mining ended in December 2006. The exploitation is presented in Figure 1. The area can be divided into three distinct zones (A, B and C) according to their pillar dimensions. Pillars in Zone B were originally larger but they have been split as part of the sweeping process. The direction of advance was from Zone A to Zone C.

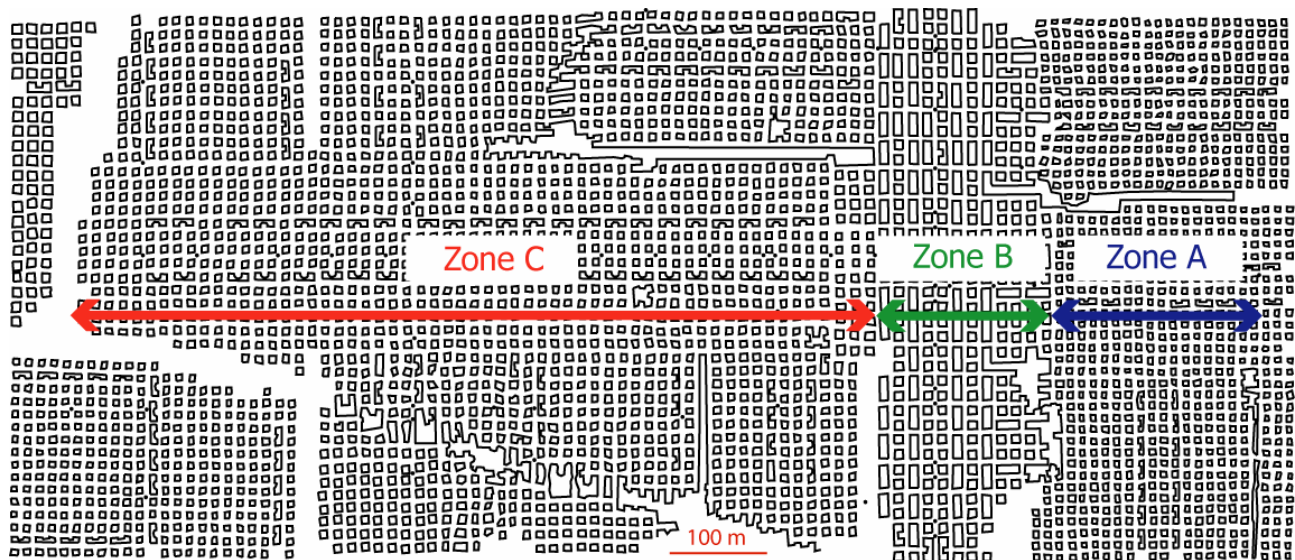


Figure 1. Area of study.

Following an underground visit in November 2006, widespread roof falls and substantial pillar scaling were observed in some areas. The scaling rate was investigated and a reasonable agreement was found in comparison to the predicted one (van der Merwe, 2003b). It should be noted that, as a consequence of the fact that the mine had changed ownership twice in the last decade, all the information required for such an investigation was not at hand. In particular, the original mining maps are no longer available. All that could be founded were digitalised versions of the plans that were supplied by the mine during a previous investigation. Such a situation is common in France

where most mines are very old and information are usually missing. In our case of study, the mine was then requested to measure the road widths and heights and subsequently supplied that information measured over 80 splits. These were then compared to the original dimensions from digitalised plans.

The concrete objectives of that study are the followings:

- Estimate the current stability of the mining area and evaluate the impact of a reduction of the pillars dimensions on the global stability;
- Estimate the long term stability of the workings;
- Complete the approach that is used in South Africa by the integration of uncertainties and expression of probabilities in order to tend towards a real assessment of “hazard”.

The methodology that has been used to reach those objectives may be detailed in several steps:

- a “local” study: the stability of a single pillar from Zones A, B and C is assessed and the “most critical” area is then identified;
- a “regional” study: the impact of the failure of a single pillar on the whole mining area is investigated;
- a “temporal” study:
- remedial actions are finally proposed in order to answer the initial objectives of the study.

3. Pillar stability assessment

The conventional methods used to assess the stability of mine pillars are based on deterministic (empiric or analytic) approaches. They usually adopt the Safety Factor (SF) as an indicator of the stability of the pillar. This Safety Factor is defined as the ratio of the pillar strength over the mean vertical stress acting on pillar. Theoretically, a SF value greater than 1 means the system is stable while a SF value lower than 1 means it is unstable. In practice, a threshold value higher than 1 is generally used at the design level to incorporate uncertainties. The stress acting on the pillar is generally determined using the Tributary Area Theory which considers the total overburden load directly over the pillar and the portion of the galleries at its perimeter. The long term strength of a coal pillar has been investigated in South Africa in several research works. Three different formulae that all integrate the width-to-height ratio of the pillar (Salamon and Munro, 1967; Bieniawski, 1968; van der Merwe, 2003a) will then be used in that study.

While practically using this approach, it appears that input data as well as formulae are uncertain. This is partly due to the nature of the system being studied which is highly concerned by natural variability (spatial and temporal). However, this uncertainty also results from a lack of knowledge about the data and about the mechanisms of failure, usually named ‘*epistemic uncertainties*’.

Cauvin (2007) presents a methodology that can be used in order to integrate different natures of uncertainties. It basically consists in performing Monte Carlo simulations in which data as well as models are considered as random values. Using such a methodology may allow to integrate in this study (1) the existence of several models to estimate the strength of a mining pillar, (2) the fact that each model combines the input data in a certain manner and that it only allows to approach reality in an approximate way, (3) the uncertainty on the parameters that calibrate models, and (4) the uncertainties on input data that are integrated in models. It also allows to estimate p_f , the probability of ‘*unsatisfactory performance*’, defined as the probability that the computed safety factor is less than the target value of stability, i.e. 1.

Table 1 presents the characterisation of the input parameters as well as the results of the stability assessment of pillars from Zones A, B and C. The mean values and the standard deviation have been determined from the analysis of the measures realized on 80 splits, or from the interpretation

of topographic maps. Coefficient of variation of model parameters have been assumed to equal 10%.

Table 1. Input parameters, Safety Factors and probability of '*unsatisfactory performance*' for the 3 Zones of the studied area (mean value and (standard deviation)).

Parameter	Distribution	Zone A	Zone B	Zone C
<i>General parameter</i>				
Number of pillars		18	16	46
Age (years)		25	44	31
<i>Input data</i>				
Pillar width (m)	Normal	5.4 (0.3)	8.5 (0.5)	6.2 (0.4)
Pillar centre (road + pillar width) (m)		12	15	14
Pillar height (m)	Normal	3.2 (0.2)	3.7 (0.4)	3.9 (0.3)
Mining depth (m)	Uniform	29 (0.9)	36 (2.3)	45 (2.9)
Volumic weight (kN.m ⁻³)	Normal	25 (2)	25 (2)	25 (2)
<i>Model parameter</i>				
<i>Salamon & Munro (1967)</i>				
K	Normal	7.2 (0.72)	7.2 (1.4)	7.2 (1.4)
A	Normal	0.5 (0.05)	0.5 (0.1)	0.5 (0.1)
B	Normal	0.7 (0.07)	0.7 (0.1)	0.7 (0.1)
<i>Bieniawski (1968)</i>				
a (Mpa)	Normal	2.8 (0.28)	2.8 (0.6)	2.8 (0.6)
b (Mpa)	Normal	1.5 (0.15)	1.5 (0.3)	1.5 (0.3)
<i>Van der Merwe (2003a)</i>				
k (Mpa)	Normal	3.5 (0.35)	3.5 (0.7)	3.5 (0.7)
<i>Result</i>				
Safety Factor		1.72 (0.38)	2.63 (0.61)	1.05 (0.25)
p _f (%)		0.3	0	48.2

From Table 1, pillars in Zone C appear to be in an unstable state. Their Safety Factors are indeed close to 1 and their probability of '*unsatisfactory performance*' is high. An analysis of variance has been carried out to complete those results. Table 2 presents the relative influences of each of the different sources of uncertainties on the total variance of the Safety Factor computed for a pillar in Zone C. 45% of the variance is explained by the uncertainties on data whereas 55% are explained by the use of models and the uncertainties existing on the parameters that calibrate those models.

Table 2. Nature and influence of the various sources of uncertainties on the computed Safety Factor of a pillar in Zone C.

Parameter	Nature of uncertainty		Variance	Variance / Total variance
	Spatial variability	Lack of knowledge		
<i>Input data</i>				
Pillar dimensions	X		0.017	28%
Mining depth	X	X	0.005	8%
Volumic weight	X	X	0.006	9%
<i>Models</i>				
<i>Model parameters</i>				
Salamon & Munro (1967)		X	0.013	21%
Bieniawski (1968)		X	0.001	2%
Van der Merwe (2003a)		X	0.003	6%
<i>“Reliability” of models</i>		X	0.016	26%

The scattering of SF values may be explained by a lack of knowledge as well as by the existence of spatial variability in some data (Table 2). Therefore, in order to interpret the value of p_f (48.2%) for pillars in Zone C, that is "linked" with the variance of SF , it is important to distinguish between the part of the final variance that is due to natural variability and the part which is due to epistemic uncertainty.

Table 2 allows doing that. The variance explained by a spatial variability only concerns in our study the input data, namely the geometrical and mechanical properties of the mining workings. It varies between 0.017 and 0.028. If we want to give a practical meaning to the p_f value, only the "variability part" of the variance has to be taken into account and interpreted (Cauvin, 2007). Therefore, using the hypothesis that the Safety Factor is lognormally distributed, and that the mean value is 1.05, the frequency of pillars that may be expected to be in a unstable state ranges between 43 and 45%, corresponding respectively to a variance of 0.017 and 0.028 (figure 2). The practical implications of that is that almost 4 pillars on 10, anywhere in the area, have a SF value less than 1.

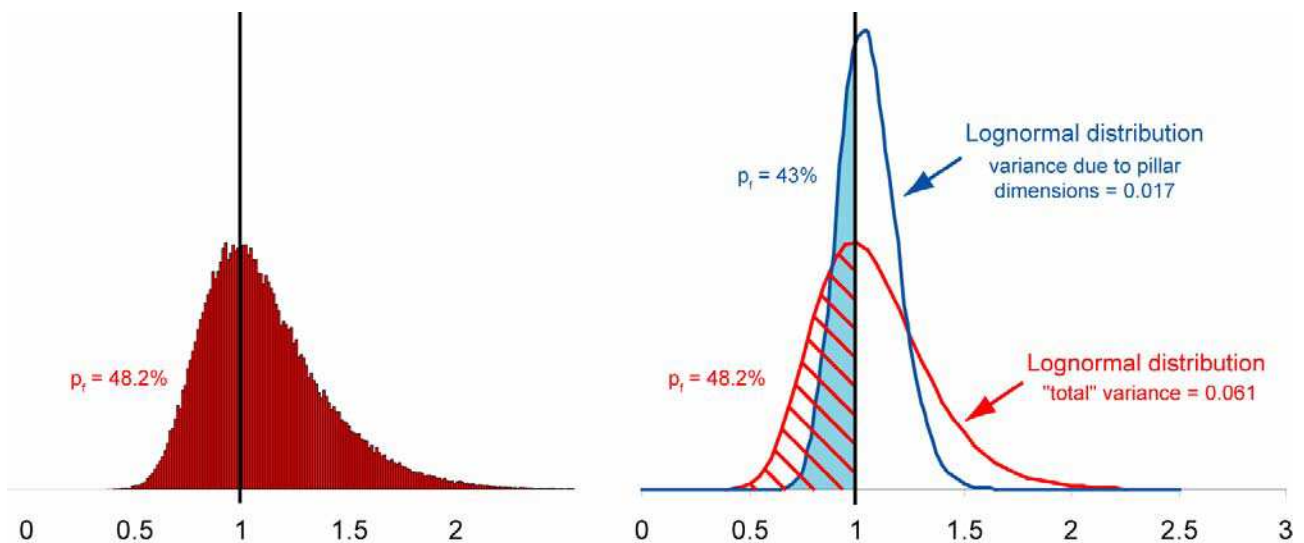


Figure 2. Interpretation of the probability of 'unsatisfactory performance'.

4. Consequences of a pillar failure in Zone C

In order to determine the consequences of a pillar failure occurring in Zone C for the whole mining environment, the *mode* of pillar failure must be investigated. This *mode* is indicated by the post failure modulus, which is in turn linked to the width-to-height ratio of pillars (van der Merwe and Madden, 2002). The post failure modulus can be estimated at a value of -2.05 GPa in Zone C. The implication of such a negative figure is that it means that once failure has been initiated, there is sufficient energy in the system to drive the continuation of the process without the addition of additional energy. The failure process is thus expected to be continue rapidly, resulting in what is commonly called a pillar run. Using the French terminology, the consequence of such a pillar collapse will be the apparition of a “brutal surface collapse”.

The process of failure can spread to others areas if the load is transferred to unfailed pillars. This can only happen if the overburden does not fail, because if it does, there is no continuity in the overburden to transfer load to adjoining areas. During former stooping trials at the mine, it was observed that the overburden had a tendency to hang up periodically. Consequently the potential for load transfer exists. The only way to estimate the magnitude of load transfer is by numerical modelling. The model chosen for this was LAMODEL, a pseudo 3-dimensional boundary element code (Heasley, 1988).

A first calibration modelling led to results close to the current situation with Safety Factors of approximately 1.0 in Zone C and 2.3 in Zone B. A second simulation was then done by artificially weakening pillars in Zone C to create a reasonable situation where they had already failed. As a result, the stress on the larger pillars of Zone B increases to 7.5 MPa and their Safety Factors decreased to 1.1. Those pillars would therefore also be subject to failure and would not be able to stop the pillar run. Figure 3 illustrates the areas the potential directions of a pillar run initiated in Zone C.

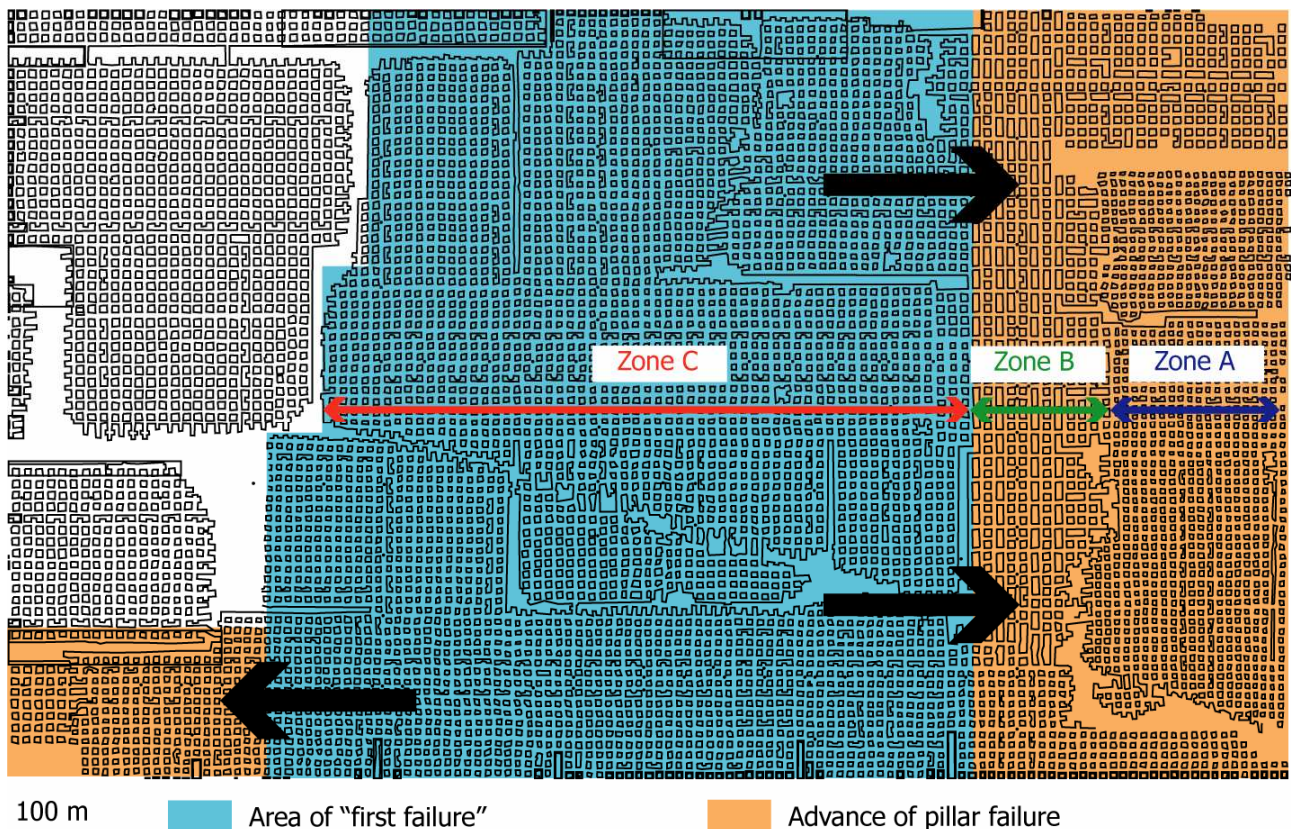


Figure 3. Potential for a pillar run initiated in Zone C.

5. Risk management

From a problem which seemed only to relate to Zone C, it has been shown that the whole mining area could be affected by pillar failures. The problem is all the more problematic as a pillar run could occur and consequences regarding the safety of miners or, at a longer term, for people or infrastructures settled in the vicinity of the mine could be expected. In such a context, it appears particularly important to integrate a temporal dimension to this analysis and to try to *forecast* when the collapse can occur. This ‘time’ factor may have direct consequences on decisions that will be taken.

The literature appears relatively poor concerning the integration of time into risk analyses related to the wide topic of geotechnical issues. Two strategies appear however possible. The integration of time in the study may be done either *directly*, through the introduction of a temporal parameter in the mechanical models being used, or *indirectly*, through a study of similar events that occurred in the past. The two strategies have been used in the paper.

Van der Merwe (2003b) developed a formula to evaluate the life of coal pillars. This empirical formula is based on the observation that the scaling process highly contributes to the weakening of pillars over time. Scaling is thus integrated in the mechanical modelling of pillar failure through the introduction of a reduction of pillar dimensions at a constant annual rate. Using a database of failed pillar in South Africa, a statistical analysis can be performed and a formula to assess life expectancy of pillar can be determined. Life of pillars in Zone C may be evaluated to be 70 years in this study.

The analysis of collapse events that occurred in the past in similar mining and geological contexts may also be performed to precise this result. Figure 4 presents the repartition (over time) of 31 pillar failures that occurred in the Witbank Coalfield since 1919. It should be noted that some failures appear very early after mining whereas others occurred later. For Carter and Miller (1996), the first failures are due to mining “defects” while the last may be explained by “wearing out” effects. In a context of post-mining management, the last type of failures must therefore be analysed.

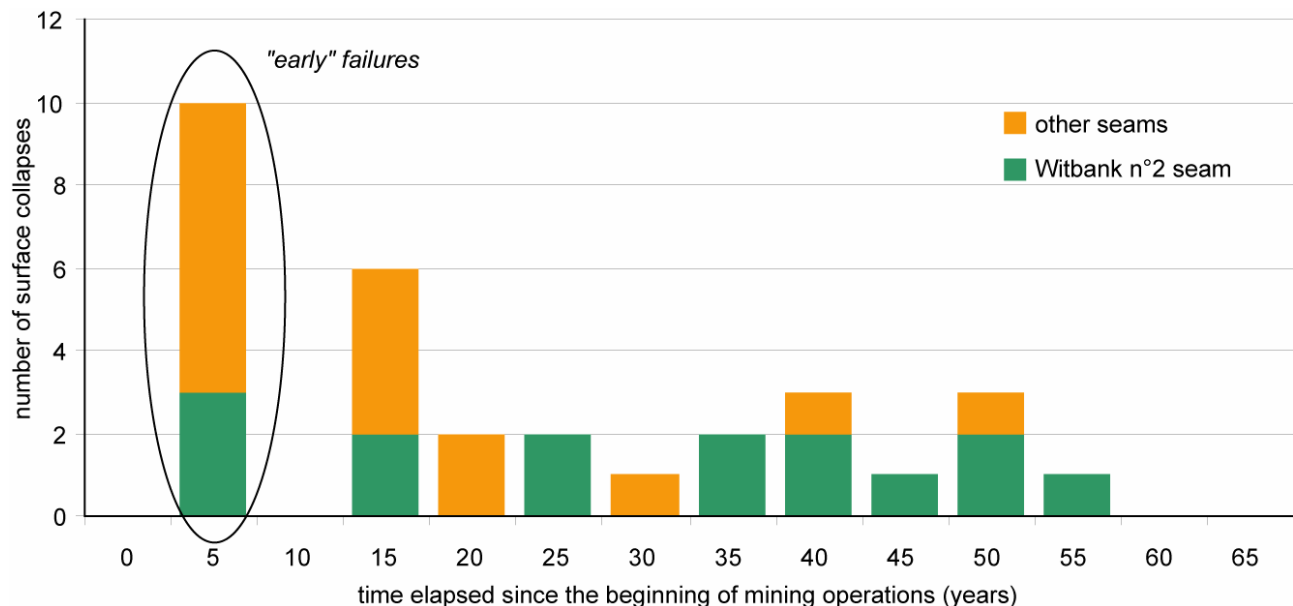


Figure 4. Number of pillars failure VS time elapsed since the beginning of mining

The small number of events (21) makes it difficult to perform a real statistical analysis of the database and to develop a temporal model to assess the probability that a pillar failure occurs over time after the end of mining. Practical qualitative conclusions may however been drawn from the analysis of Figure 4. Firstly, it appears that pillar failures occurs later when seam n°2 of the

Witbank sequence has been mined. Secondly, no “average” life can be identified. That signifies that a collapse can occur at anytime. Thirdly, a pillar failure can still occur 52 years after mining ended. Zone C, in which mining of the seam n°2 started 31 years ago, is thus currently particularly concerned by the phenomenon of pillar failure.

The two methods allowing to estimate the possible date of a pillar failure lay on very empirical methods and must be interpreted with a lot of care. The formula proposed by van der Merwe (2003b) has for example a confidence level that does not exceed 80%. Moreover the communication of its results to mining engineers may appear delicate as those latter may not be very familiar with statistical analyses. The practical meaning and application of results that have been obtained using statistical tools is still difficult for many actors working in the field. Adding another method of analysis into the problem may therefore, if the two methods correlate, give a supplementary weight to the results. This is the case in that study.

6. Technical recommendations

This study has shown that even if Zones A and B are stable at the time of the analysis, a failure in Zone C may have consequences on the whole area. Due to the presence of important spatial variability in the area, such a failure can occur everywhere in Zone C. Two temporal analyses have even illustrates that a pillar failure is likely to occur in a small amount of time.

The practical implications of those conclusions are that workings must be stopped and abandoned in the studied area. In a short term, the implementation of a monitoring system aimed at protecting the crews working in the other sections is essential. “Reverse extensometers” installed from the surface into a borehole drilled through a pillar and anchored in the rock below the pillar will for example allow to monitor any compression in a pillar and can be used to trigger an alarm.

Actions have also to be taken in order to protect the population and the infrastructures that may settled above the workings at a longer term. In France, in order to post and manage the consequences of the events induced by a past mining activity, the French Ministry in charge of Industry has charged several actors to elaborate Mining Risk Prevention Plans. Those are aimed at identifying hazards and risks that may affect old mining areas and at defining rules for urban development and for land and water use management (Didier and Leloup, 2005). Such a scheme of methodology may be applied in the South African context in order to define technical regulations concerning the mine being studied.

7. Conclusions

The joined study between France and the Republic of South Africa presented in this paper constitutes a real opportunity at realising an exchange of knowledge and a strengthening of the current skills of the two countries. The mining induced hazard assessment made at the studied mine has indeed taken advantages from the mining and geomechanical South African knowledge as well as from the French experience in terms of the management of the post-mining issues.

In addition to the practical results that may be obtained concerning the studied mine, more conceptual questions have also been tackled. The use of probabilities and the concrete meaning of the probability of unsatisfactory performance have thus been discussed. An emphasis has been laid on the importance of communication between the geomechanical expert in charge of the hazard analysis and the stakeholders, either the mining company or the Authorities. The evaluation of the

place and the time of the possible failure appears therefore essential for a better hazard management and a good planning of the future land use.

8. Acknowledgements

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